RL-TR-96-189
Final Technical Report
December 1996

NOVEL OPTICAL FIBERS AND DEVICES

Brown University

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Rome Laboratory
Air Force Materiel Command
Rome, New York

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1996	**FINAL, May 95 - May 96**

4. TITLE AND SUBTITLE
NOVEL OPTICAL FIBERS AND DEVICES

5. FUNDING NUMBERS
C - F30602-95-C-0092
PE - 62702F
PR - 4600
TA - P4
WU - PP

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Rome Laboratory/OCPA
25 Electronic Pky
Rome NY 13441-4515

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
RL-TR-96-189

11. SUPPLEMENTARY NOTES
Rome Laboratory Project Engineer: James M. Battiato, OCPA, (315) 330-3737

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

We have engaged in the development of gas and liquid sensors using the technique of intra-cavity laser spectroscopy. When the gain is spoiled by placing an absorber within a laser cavity, and the absorption signature corresponds to the lasing line, significant enhancements of absorption occur. As a consequence of the high reflectivity of the cavity, photons make many passes before exiting the cavity, and the effective absorption length of the cell within the cavity is significantly increased. In addition, modal considerations can further enhance the sensitivity of such measurements, so that the effective length of the cavity is increased by many orders of magnitude. Such experiments are usually carried out in a laboratory environment. By taking advantage of recent advances in fiber lasers and fiber Bragg gratings, it is possible to obtain spectroscopic accuracy in a device the size of a fountain pen. This is done by placing an absorption cell within a fiber laser cavity and compression tuning the Bragg grating that defines he cavity. This is a narrow band instrument that depends on the existence of an absorption signature under the gain bandwidth of the fiber laser. Preliminary experiments have been carried out using acetylene.

14. SUBJECT TERMS	15. NUMBER OF PAGES
fiber laser, fiber sensor	20
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UNLIMITED**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Abstract

Work of the past year has centered on several topics. Preliminary work has studied the effects of co-doped optical fiber lasers fabricated by a special technique developed at the Laboratory for Lightwave Technology at Brown University, and work is in progress in this area. We have also engaged in the development of gas and liquid sensors using the technique of intra-cavity laser spectroscopy. There are several sensor applications of interest to the Air Force in which this technique may have specific advantages.

When the gain is spoiled by placing an absorber within a laser cavity, and the absorption signature corresponds to the lasing line, significant enhancements of absorption occur. As a consequence of the high reflectivity of the cavity, photons make many passes before exiting the cavity, and the effective absorption length of the cell within the cavity is significantly increased. In addition, modal considerations can further enhance the sensitivity of such measurements, so that the effective length of the cavity is increased by many orders of magnitude. Such experiments are usually carried out in a laboratory environment. By taking advantage of recent advances in fiber lasers and fiber Bragg gratings, it is possible to obtain spectroscopic accuracy in a device the size of a fountain pen. This is done by placing an absorption cell within a fiber laser cavity and compression tuning the Bragg grating that defines he cavity. This is a narrow band instrument that depends on the existence of an absorption signature under the gain bandwidth of the fiber laser. Preliminary experiments have been carried out using acetylene.

I. Introduction

Techniques by which spectroscopic information on gases and liquids may be obtained are conventionally associated with experiments performed in a laboratory; however, there are innumerable situations in which it is of interest to have a small, hand held device that can make such measurements. This is the focus of this research.

Spectrometers, FTIR (Fourier Transform Infra-Red) spectroscopy, and gas chromatography are all instruments□capable of measurements over a wide bandwidth. These devices are naturally laboratory instruments, although efforts are being made to

modify and ruggedize them for field use. In the following, we will consider a narrow band application of spectroscopy that has the possibility of resulting in a low price, small device that possesses the capability of high resolution spectroscopic measurements.

II. FLICS: Fiber Laser Intra-Cavity Spectroscopy

In traditional spectroscopic measurements, a specific wavelength is sent through the sample, and, in accordance with Beer's law, exponential attenuation of the beam results.

$$\frac{I}{I_o} = \exp(-\alpha L)$$

In this equation, I is the intensity, L is the absorption path length, α is the absorption coefficient, and I_o is the intensity. Particle concentration, absorption cross section/molecule and pressure influence the absorption coefficient. Increases in sensitivity of detection can be achieved through the use of a longer interaction path length, or through the use of an appropriate White cell, which is arranged to allow many passes through the absorbing medium.

An alternate technique that has been used in the laboratory for many years is to place the absorber directly within the lasting cavity itself. Experiments using Hg vapor have shown that detection sensitivity can increase by five orders of magnitude. [1] In these early experiments, a dye laser pumped by a visible laser was employed. More recently, a Nd optical fiber laser with bulk mirrors has been used for the sensitive detection of water vapor, with an equivalent path length of 10 km. [2]

There are two different conditions that apply. The first of these is one in which the laser line width >> Absorber line width

$$\text{Enhancement} \propto \frac{2n\delta}{\left[\text{Log}\left(1/R\right)+\xi\right]\left[\delta-\text{Log}\left(1/R\right)-\xi\right]}$$

where

δ = Gain

ξ = Losses

n = # of modes

R = Reflectivity of the mirrors

The second condition is that in which the laser line width << Absorber line width

$$\text{Enhancement} \propto \frac{2\delta}{\left[\text{Log}\left(1/R\right)+\xi\right]\left[\delta-\text{Log}\left(1/R\right)-\xi\right]}$$

The enhancement in both cases refers to an effective increase in an effective absorption coefficient. In both cases, enhancement of detection sensitivity is enhanced if losses are small and mirror reflectivity is high. The physical explanation for this is analogous to the application of a White cell, i.e., photons make many passes through the absorbing medium before exiting the laser, and the effective absorption path length can be significantly increased. For an output coupler of 99.9% reflectivity, this would be three orders of magnitude. In addition, if the laser is operated near threshold, there will be significant increases in detection sensitivity. This will be offset, in part, by a decreased signal/noise ratio.

The first case, that in which the laser linewidth >> than the absorption line width has an additional factor, n, the number of modes. We consider longitudinal modes, where the modal separation is equal to the square of the wavelength divided by 2nL. This number can be many tens of thousands. Thus, a homogeneously broadened laser operating at a single frequency will have many modes. If an absorber attenuates any one of these modes, all of the modes will be extinguished. For this reason, the detection sensitivity for this case can be quite large, and the effective absorption cross section can be many orders of magnitude larger than that found in Beer's law.

In the following, we take advantage of a recent development in photonic technology: the fiber optic Bragg grating. Using intense UV light, typically at 244 or 248 nm, defect centers can be induced in a germanium doped glass that causes an associated density increase in the glass. [3] This effect is significantly enhanced if the glass is appropriately hydrogen loaded prior to exposure to UV radiation [4] To "write" a Bragg grating, a periodic intensity pattern must be imposed on the glass, and this results in a periodic structure in the glass. This, in turn, causes a reflection of the guided wave in an optical fiber if the grating periodicity corresponds to the wavelength of the light. This is the same as the Bragg condition in crystalline

structures. There are several techniques by which these gratings may be produced, but the most convenient is through the use of a phase mask, as shown in Figure 1. In this case, UV light impinges normally on the phase mask, and an optical fiber is placed directly under the mask. Direct light is canceled (there may be as little as 3% light intensity in zeroth order), and most of the energy can be channeled into the first order diffraction. The intersection of the + and - first orders of diffraction causes an alternating intensity pattern that leads to a periodic densification of the core of the optical fiber. This results in a "mirror" in the core of the fiber. In Figure 2 is shown the reflection spectrum of a fiber Bragg grating mirror made in our laboratory and its response to compression tuning. The disadvantage of this technique is the limitation to a small tuning range below the wavelength at which the phase mask is written. This is accomplished by stretching the fiber during the "writing" process. [5]

In Figure 3 is shown the configuration used for the analysis and experimental verification of FLICS. The laser cavity is defined by the Bragg grating mirror and the 100% reflecting mirror. There is an intra-cavity absorption cell that contains the gas to be measured, and the laser is pumped, ideally, by a diode laser some distance away. The return path of light is also coupled by means of a y-splitter to a detector. This configuration is appropriate for the detection of any gas that has an absorption signature under the gain bandwidth of the optical fiber laser. Tuning of the Bragg grating may be accomplished in the following manner. If the Bragg grating section of the optical fiber is glued to a flexible support, when that support is bent with the fiber on the concave side, the fiber is compressed. This compression may be readily obtained, and we have been able to compression tune a fiber Bragg grating mirror by 20 nm. Thus, the instrument that we propose is a substance specific, narrow band device. Work in the future will consider the Tm or a Tm-Ho optical fiber laser that has a gain bandwidth (depending on the detailed nature of the glass host) that extends from 1,650 nm to 2,010 nm. Many gases of interest have absorption signatures (in some cases higher overtones) in this region of the spectrum.

At the present time, we only possess the capability to make fiber Bragg gratings in the 1550 nm region, because this is the wavelength at which our phase mask is written. Work is in progress to frequency double our argon ion laser with an external cavity so that 244 nm

photons can be obtained from this source. For this reason, we have demonstrated the principles of FLICS using an erbium fiber laser (gain bandwidth from 1535-1550 nm) in conjunction with acetylene, which as an absorption signature in this region of the spectrum.

III. Experimental Results

In Figure 4 we show the absorption spectrum of acetylene taken with an Ando spectrum analyzer and a 1550 LED as the light source. Using approximately 30 cm of fiber into which a 90% Bragg grating is written, we see in Figure 5 the output of the fiber laser for the case in which there is no absorbing gas within the intra-cavity cell. It is seen that there is 50 dB of gain for the lasing line, and, as noted above, this line can be compression tuned over 20 nm. If acetylene is introduced into the gas cell, and if the laser line is tuned to 1538 nm, which lies between two adjacent lines of acetylene, then we obtain the results shown in Figure 6. There is no diminution in the intensity of the lasing line, but, from the fluorescent side bands, we can clearly distinguish the various rotational lines of the acetylene. If, by bending the flexible member to which the Bragg grating is attached, we compression tune the Bragg grating to 1539.12 nm, we see a complete extinguishing of the gain within the cavity. This is shown in Figure 7. In these experiments we have used a Ti-Sapphire laser pumped by an argon ion laser to obtain a 980 pump source. This was done because a pigtailed diode laser at this wavelength was not available to us. Such a source would have been adequate to pump the erbium fiber, since our fiber laser in this cavity configuration had a threshold of 2 mW.

Preliminary experiments on the pressure sensitivity of this sensor have been carried out with acetylene. The gas cell was pumped down and in Figure 8 is shown the intensity signal as a function of gas pressure in the intra-cavity cell. The sensitivity of the measurement is, at present, severely limited by several factors: i.e., the stability of the laser pump source, the losses within the cavity, and the relatively small number of longitudinal modes. With a diode source, a square wave could provide the equivalent of a lock-in amplifier, so that simple signal processing techniques could be used.

IV. Future Work

Experiments have thus far been limited to acetylene, since we have the capability of writing Bragg fiber gratings in the 1535-1550

nm region of the spectrum. Work is in progress to frequency double our argon ion laser so that Bragg gratings may be written at arbitrary wavelengths. In particular, emphasis will be placed on the detection of new classes of refrigerant gases and gases used to extinguish fires, many of which have absorption signatures under the gain bandwidth of the Tm or the Tm-Ho fiber laser, i.e., in the 1.8 micron range [6-9]. These lasers can be pumped with relatively inexpensive diode sources. Effort will also be placed upon using a square wave source for the pumping laser, so that convenient lock-in techniques can be used to offset any problems of laser stability.

V. Conclusions

A convenient instrument for the narrow band spectroscopic detection of gases has been proposed and demonstrated. This involves a fiber laser oscillator defined by a 100% reflecting mirror and a highly reflective fiber Bragg grating mirror used as the laser output coupler. The laser can be diode pumped, and we have demonstrated a threshold of only 2 mW. Any material that has an absorption signature under the gain bandwidth of a fiber laser is a good candidate for such a device; however, due to our present ability to write Bragg fiber mirrors only in the 1550 nm regime, we have focused on the detection of acetylene as a model experiment. Acetylene was chosen because it absorbs in the 1540 nm region, which can be accessed by the erbium fiber laser. Future work will concentrate on the Tm, and Tm-Ho systems, which have a gain bandwidth extending from 1,650 to 2,010 nm. Also, we will consider the Nd system, which lasses at 1,060 nm. Many gases have absorption overtones in these wavelength regions.

VI. References

[1.] T. Haensch, A.L. Schawlow, P. Toschek, "Ultrasensitive Response of a CW Dye Laser to Selective Extinction", IEEE J. of Quant. Elect., **QE-8**, 802(1972).

[2.] A. Boem, A. Stephan, V.M. Baev, and P.E. Toschek, "Intracavity absorption spectroscopy with a Nd^{3+} doped fiber laser", Optics Letters, 18, 1955(1993).

[3.] K.O. Hill, et al., "Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask", Appl. Phys. Lett., 62 10(1993).

[4.] P. J. Atkins, et al., "Mechanisms of enhancing UV photosensitivity via hydrogen loading in germanosilicate glasses", Electron. Letters, 29, 1234(1993).
[5.] Q. Zhang, D. Brown, L. Reinhart, and T.F. Morse□, "Tuning Bragg wavelengths by writing gratings on pre-strained fibers", IEEE Photonics Letters, Vol. 6, No. 7, September 19943.
[6.] W.L. Barnes and J.E. Townsend, "Highly tunable and efficient diode pumped operation of Tm^{3+} doped fiber lasers", Optics Letters, 1990.
[7.] D.C. Hanna, et al., "Efficient high-power continuous-wave oscillation of a monomode Tm-doped fibre laser at 2 microns pumped by a Nd:YAG laser at 1.06 microns", Optics Letters, 1989.
[8.] D.C. Hanna, et al., "Continuous wave oscillation of a monomode thulium doped fibre laser", Electron. Lett., 1990.
[9.]. Kyuhngwhan Oh, T.F. Morse, L. Reinhart, and A. Kilian, "Continuous wave oscillation in Tm-Ho co-doped silica fiber", Optics Letters, Vol. 19, no. 4, February 1994.

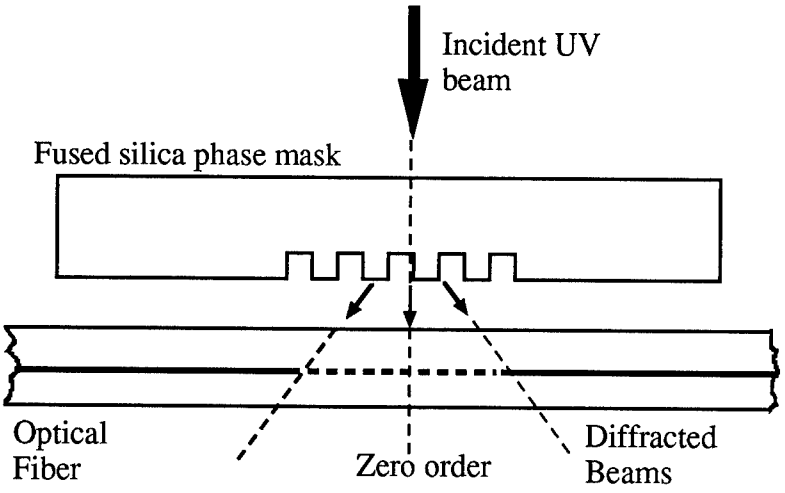

Figure 1. Phase Mask for Bragg Grating.

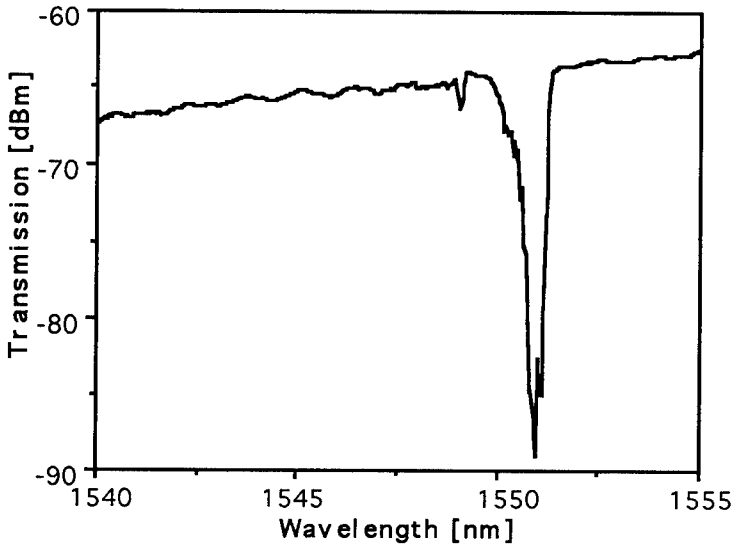

Figure 2. Fiber Bragg Grating Mirror.

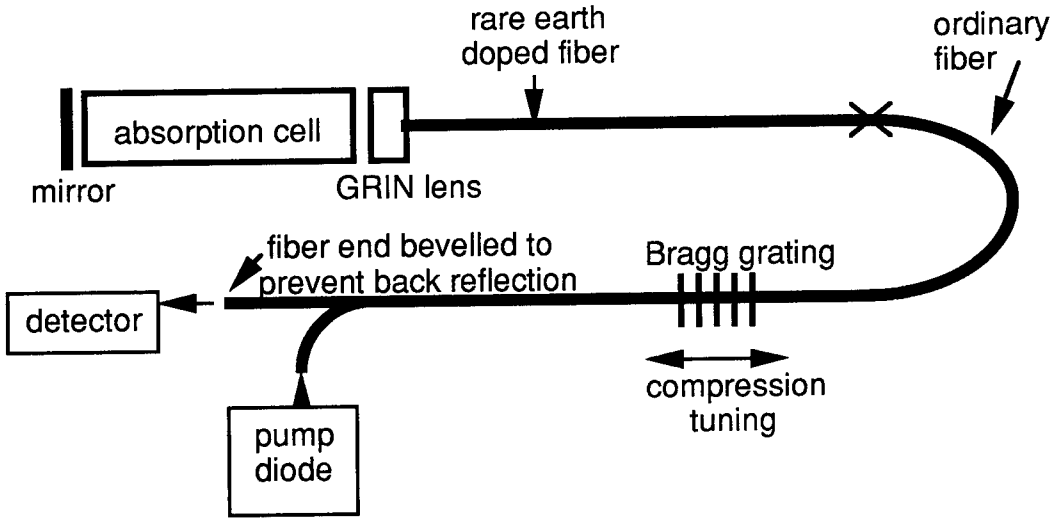

Figure 3. Configuration for FLICS.

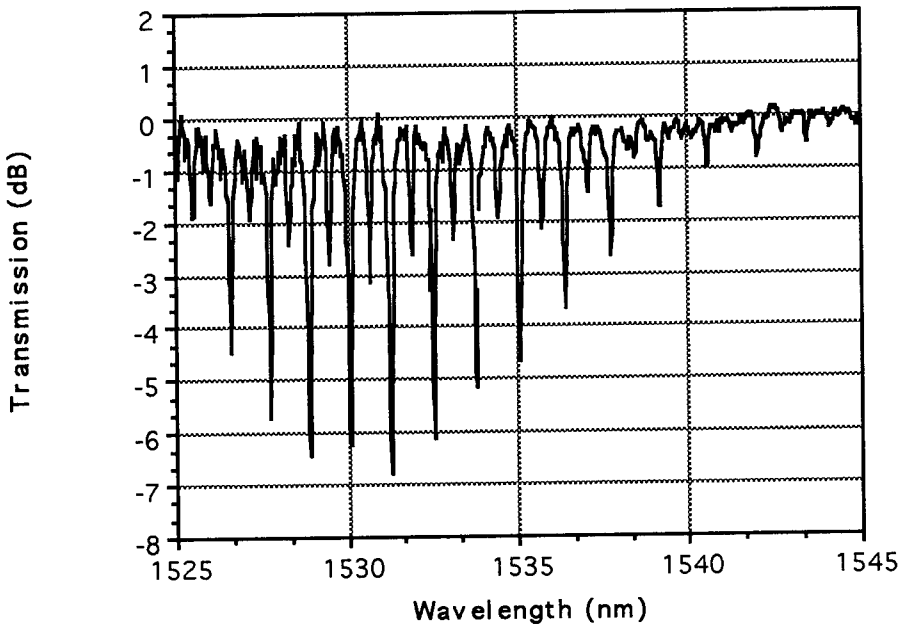

Figure 4. Absorption Spectrum of Acetylene.

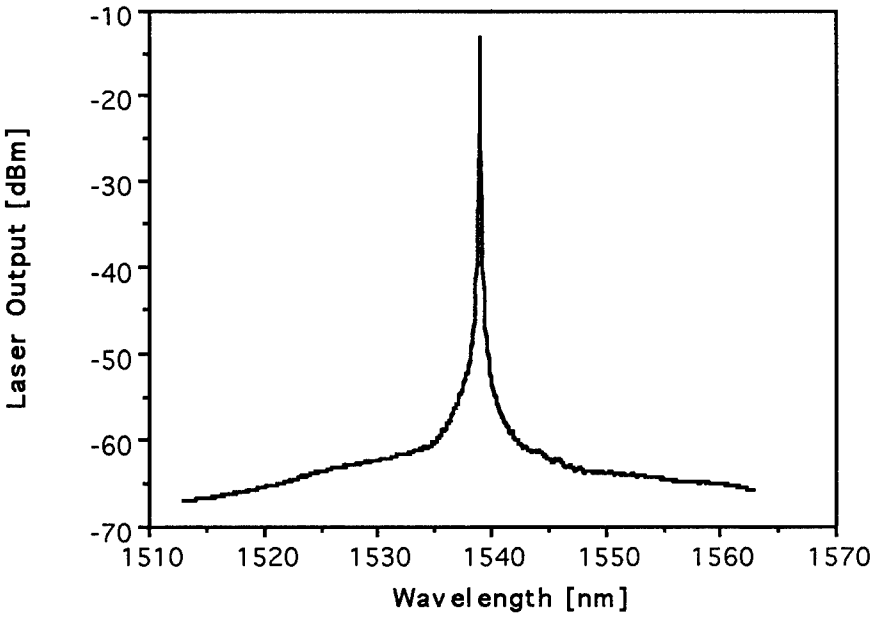

Figure 5. FLICS output, no gas in cell.

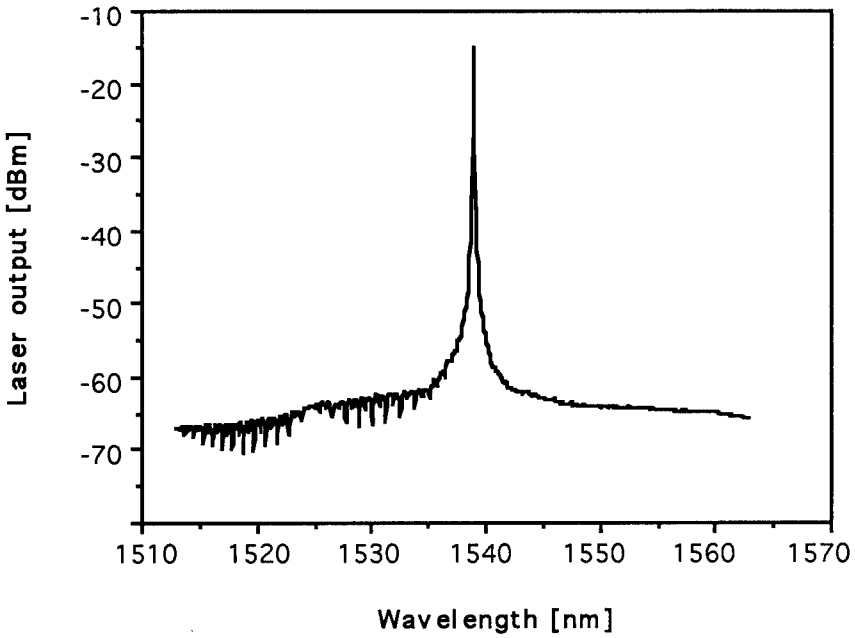

Figure 6. Absorption with laser tuned between acetylene lines.

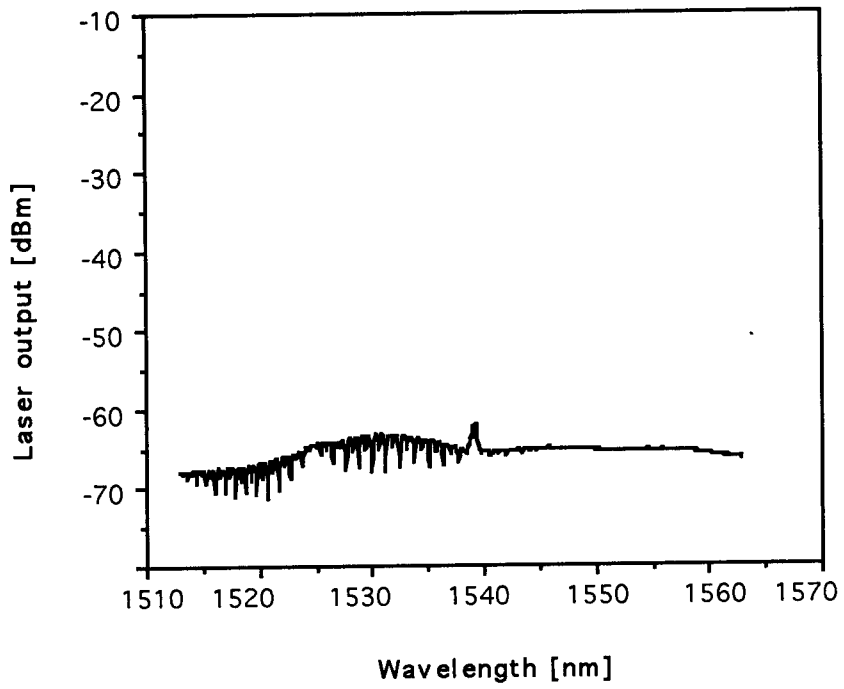

Figure 7. Laser tuned to acetylene line.

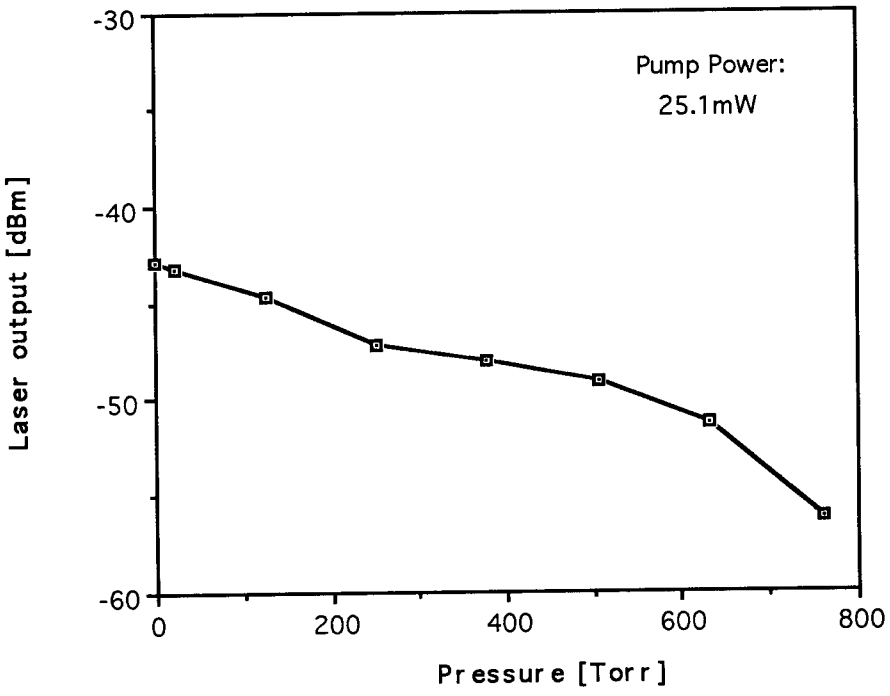

Figure 8. Sensitivity as a function of gas pressure.

*U.S. GOVERNMENT PRINTING OFFICE: 1997-509-127-47082

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